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NOAA LONG-TERM RESEARCH PROGRAM PLAN

THORPEX:

A GLOBAL ATMOSPHERIC RESEARCH PROGRAM

NOAA THORPEX Science and Implementation Team

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1. EXECUTIVE SUMMARY

THORPEX AND NOAA'S STRATEGIC GOALS. The overarching goal of NOAA's THORPEX Program is to significantly accelerate improvements in weather forecasting in a strategic fashion over the next decade. NOAA's THORPEX Program is being developed in support of NOAA's Third Mission Goal of serving "Society's needs for weather and water information" (NOAA, 2003).

ANTICIPATED FUTURE NEEDS. During the last few decades of the twentieth century, economic and other developments have made society more susceptible to adverse weather conditions. As a result, society is becoming more reliant on information about future weather both to avoid adverse weather losses, and to take advantage of favorable conditions. Since this trend is expected to continue and perhaps accelerate, new needs are likely to develop in terms of weather forecast information:

1) An overriding need is expected to develop for reliable information on forecast uncertainty. Since rational decision-making is contingent upon the availability of such information, forecast uncertainty information will become a basic user requirement;
2) To counteract society's ever increasing sensitivity to weather conditions, it is also expected that there will be a strong need for more detailed and more skillful forecast information.

CURRENT STATUS. The weather forecasting process consists of four major steps:

1) Collection of observations to properly assess the initial state of the system;
2) Assimilation of all such data into a format ("analysis") used in Numerical Weather Prediction (NWP);
3) Generation of possible forecast scenarios given the analysis and its uncertainty, using NWP models;
4) Post-processing (synoptic and statistical) of NWP forecast data and their economic or societal applications.

Traditionally, the four sub-components of weather forecasting are developed separately. As a result, the forecast process consists of somewhat disjoint steps. This poses a serious limitation on improvement both in methods and performance.

PROGRAM OBJECTIVE. THORPEX proposes to contribute to the development of a strategically new approach to forecasting. According to this new paradigm, the NWP forecast process will be:

1) Integrated. Improvements to the four sub-components will be designed, implemented, and evaluated in a coordinated fashion, based on the concept of end-to-end forecasting.

2) Adaptive. Observation, assimilation, forecast, and application procedures will vary depending on the case and forecast situation.
3) User controllable. All four components of the forecast process, if desired, will be driven by the case specific collective needs and requirements of the users.

PROGRAM ELEMENTS. These objectives will be met through a long-term research program coordinated among the four sub-areas of NWP forecasting, that will address the open scientific questions related to the development of the new NWP paradigm. The scientific questions will be addressed through a series of interconnected research and development tasks that will lead to the emergence of new NWP methods and activities.

COLLABORATIVE EFFORT. The THORPEX program is so complex, and its major goal of developing a new NWP paradigm is so ambitious, that it cannot be realized by the efforts of a single line office, agency, or even nation. Therefore, cross-cutting collaboration among different public and private research and user outlets, both on the national and international level, is critical to the success of THORPEX.

APPLICATIONS. While all THORPEX research will aim at achieving the overarching goal of developing the new NWP paradigm, individual agencies and nations are expected to focus on different areas in terms of applications. The Office of Naval Research (ONR), for example, may pursue THORPEX research applicable in a meso-scale environment, while European nations are expected to pursue research focused on the 1-3 day weather forecast range.

DELIVERABLES. Given other existing programs and activities, NOAA's primary interest in THORPEX is medium- and extended-range (3-14 day) weather forecasting over the US. The practical goal of NOAA's THORPEX program is the development of new techniques that will (1) accelerate the rate of forecast improvement over the next decade, to allow, for the first time, detailed and skillful (2) precipitation forecasts for the 3-7 day period; and (3) daily weather forecasts for the 8-14 day period, both in probabilistic form.

SYNERGISTIC EFFECTS – BENEFITS FOR NOAA. The efforts of different agencies on various applications, coordinated on the national and international level, will benefit NOAA by contributing to the overall development of the new NWP paradigm. At the same time, they will provide ready-to-use methods and techniques in application areas not covered by the NOAA effort, such as meso-scale and 1-3 day forecasting. To maximize the benefits in these application areas, the NOAA THORPEX program will collaborate closely with other NOAA and United States Weather Research Program (USWRP) programs, such as the Pacific Landfall Jets Experiment (PACJET) and the Joint Hurricane Testbed (JHT) program. Additionally, THORPEX will interface with the climate community for improved climate monitoring and for the development of a seamless NOAA weather and climate forecast suite.

SYNERGISTIC EFFECTS – NOAA CONTRIBUTIONS. In a reciprocal fashion, NOAA's THORPEX efforts will benefit other programs and agencies involved in weather forecasting activities. To further this goal, NOAA will carry out an aggressive education and outreach program on the national and international level to ensure that the benefits resulting from the new integrated, adaptive, and user controlled NWP process will reach a wide range of users, including those in less developed nations.

PERFORMANCE MEASURES. Faithful to its integrated approach, THORPEX will use a unique and comprehensive performance measure, based on the concept of end-to-end forecasting. To assess overall success, the new NWP paradigm will be evaluated based on whether the societal benefits resulting from the new forecast procedures exceed their implementation and maintenance costs.

RESOURCE REALLOCATION. Contributions from the four sub-areas will also be measured and compared to each other in the *implementation and maintenance cost vs. incremental forecast benefit* framework. This integrated THORPEX evaluation approach will permit, for the first time, a meaningful assessment of the comparative value of NWP sub-component improvements on the overall societal and economic value of 3-14 day weather forecasts. Such an analysis will provide an important input for a rational reallocation of research and operational resources to ensure that the nation has a balanced and cost effective research and operational weather forecast infrastructure.

PATH TO OPERATIONS. The new methods and activities that THORPEX will develop can benefit society only if implemented into NOAA operations. THORPEX envisages a very strong collaboration between researchers at academic and operational institutes during the course of the entire program, from design through research to delivery. This will ensure a smooth, speedy transition of results from research into operations. To facilitate such collaboration, THORPEX will establish an operational test facility where extramural research achievements can be tested and subsequently implemented into the operational environment in an efficient manner.

BUDGET. To ensure the success of its integrated effort, NOAA's THORPEX program requests a budget to fund research in all four NWP sub-components in a balanced fashion. Total requested funds are $2, $5, and $10M for years 1, 2, and 3-11, respectively. All initiatives under NOAA's THORPEX program will be peer reviewed and more than half of the requested funds will be distributed to extramural research efforts. The rest of the budget will be used to create and maintain an infrastructure essential for conducting THORPEX research, such as the enhancement of related NOAA research activities, the establishment of an Operational NWP Test Facility (ONTF) and data base, and real-time testing and demonstration of the new forecast paradigm.

2. INTRODUCTION

2.1 RESEARCH REQUIREMENTS AND NOAA'S MISSION GOAL

One of the four Mission Goals of NOAA is to "Serve society's needs for weather and water information" (Strategic Plan, NOAA 2003, also see Section 5.2). NOAA's THORPEX Research Program is being developed to ensure that the nation's evolving needs for weather and water related environmental forecasts can be adequately met in the future.

In recent decades society has become more sensitive to weather, partly due to increases in the US population, the gross domestic product, and coastal developmental activities. Today, close to one quarter of the US economy (about $2.7 trillion) is sensitive to weather. Severe storms (hurricanes, tornadoes, etc) alone cause $11 billion in damages annually. To mitigate adverse weather losses and to benefit from favorable weather conditions, individuals and organizations increasingly use information on future weather in their decision making process. The value of daily weather forecasts to the public is currently estimated to be nearly $12 billion annually.

NOAA anticipates that this trend will continue or even accelerate, resulting in an increased demand for weather and water forecast information in the future. In response, "NOAA must expand forecast and warning services" (Strategic Plan, NOAA 2003). To facilitate their wider and more efficient use, the information content of weather forecasts will have to be enhanced. On one hand, the skill of weather forecasts in general will be increased. On the other hand, new probabilistic forecast formats will be introduced to facilitate the incorporation of future weather-related information into formal user decision-making algorithms (Strategic Plan, NWS 1999). Together, these changes will significantly enhance the utility of weather and related water forecasts, and will widen the range of users who can benefit from them. THORPEX is designed to provide the scientific and technological infrastructure necessary to meet these future weather related forecast needs and challenges through a long-term international research program whose major goal is to accelerate weather forecast improvements in the coming decade.

As NOAA's operational arm of weather forecast activities, the National Weather Service (NWS) is especially interested in the success of the THORPEX program. Accordingly, NOAA's participation in the THORPEX program is guided by the Science and Technology Infusion Plan (STIP, see also Section 5.3) of the NWS, ensuring that the long term research activities are directly connected with the operational needs of NOAA.

2.2 CURRENT STATUS OF WEATHER FORECASTING

2.2.1 MAJOR FORECAST COMPONENTS

The goal of weather forecasting is to provide advance knowledge about the expected conditions of the atmosphere to interested users. Today, most weather forecasts issued in the 1-14 day time range are based on Numerical Weather Prediction (NWP) model guidance. Though human forecasters are able to add value to these numerical guidance products in many cases, past improvements seen in weather forecasts have been closely tied to improvements in NWP model guidance (see Fig. 1). Therefore, to achieve NOAA's weather forecast goals one must consider improvements to all NWP forecast procedures.

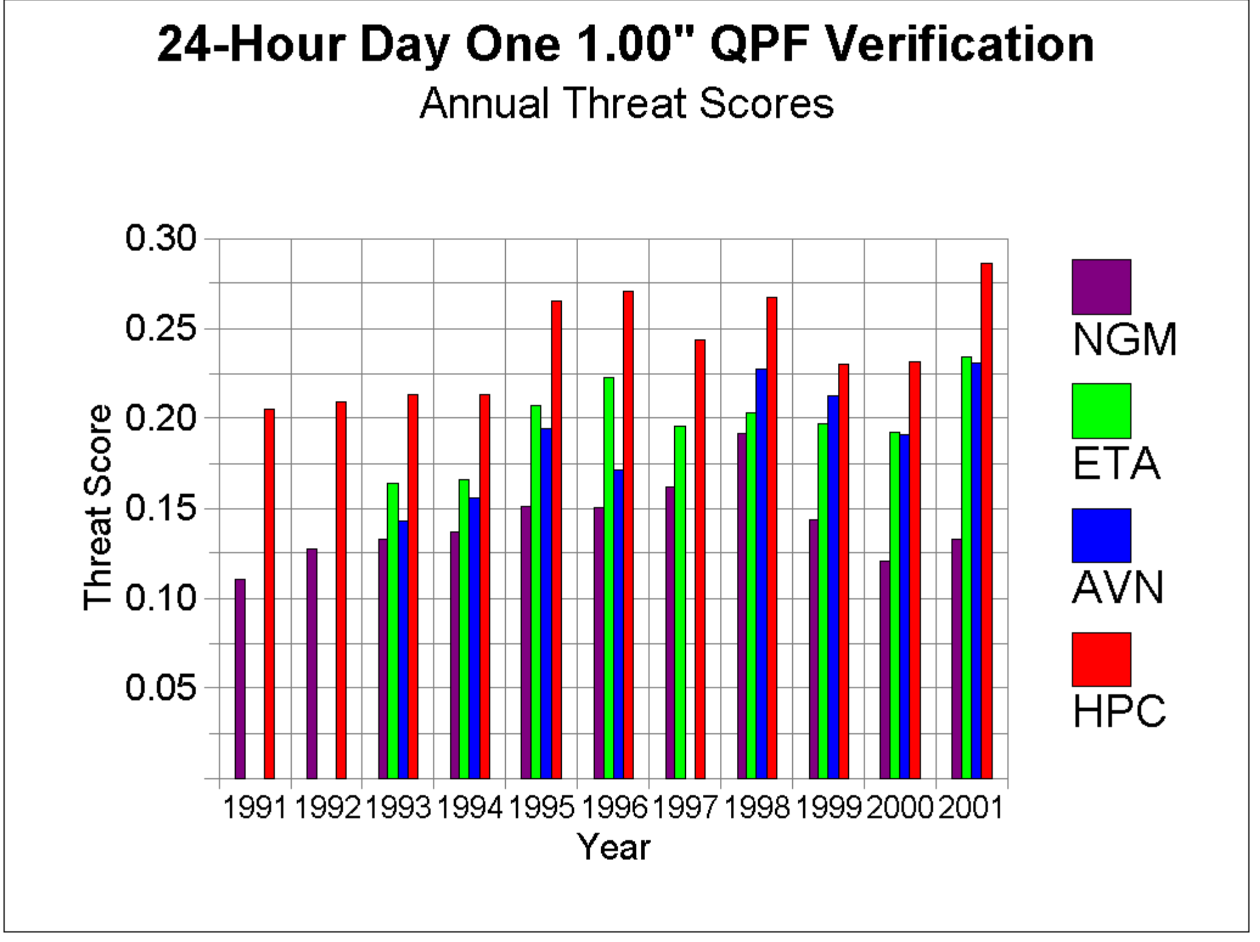

Fig. 1. Comparison of error in 24-hour accumulated precipitation forecasts made at 12-hour lead-time by three NCEP NWP models (NGM – frozen benchmark; AVN – operational global; and ETA – operational regional models) with that in the ensuing value-added official Hydrometeorological Prediction Center (HPC) forecast. Courtesy of the National Precipitation Verification Unit and HPC.

In general, the utility of NWP-based weather forecasts depends on the quality of its four main components:

1) **Observing system** of the atmosphere and its surrounding ocean and land conditions, for the collection of data used in defining the initial conditions for NWP model forecasts;
2) **Data assimilation system** that, based on the observational data and a prior NWP forecast estimate, creates the initial conditions for NWP forecasting;
3) **Forecast procedures**, including NWP modeling and ensemble techniques that generate forecast products;
4) **Applications** in various economic and societal areas. Before their final utilization by the end users, NWP forecasts are often post-processed statistically to reduce their systematic errors and are also reviewed and modified by human forecasters for further quality enhancements.

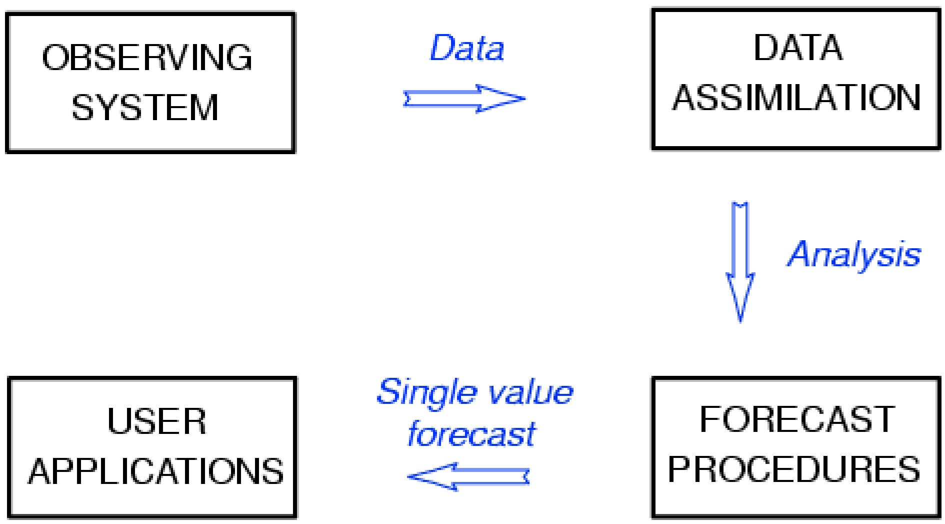

Fig. 2. Schematic diagram illustrating the one-way flow of initial value related information in a traditional NWP forecast process.

2.2.2 TRADITIONAL FORECAST PROCESS

Traditionally, the four components of NWP: the observing, data assimilation, forecasting, and application sub-systems have been developed with less than optimal coordination. This has resulted in an NWP forecast process that is largely made up of disjoint steps. For example, until recently, new atmospheric observational platforms were often developed without direct consideration of NWP data assimilation and forecast requirements. Similarly, the requirements of the forecast and application components had little or no influence on the NWP components whose input they use.

In current operations, a component in the forecast process is connected to the next sub-system by an output in the form of a single (observation, analysis, or forecast) value (see Fig. 2). For example, the quality of the initial conditions generated by data assimilation schemes was not used as input in NWP forecasting until the recent introduction of ensemble techniques. Also, apart from some special cases, users had no access to case dependent probabilistic forecast information that could have substantially enhanced the utility of weather forecasts. THORPEX recognizes that the current lack of focus on the interdependence between the various components of the NWP forecast process is a serious limit to further advances in NWP forecasting.

2.2.3 STATUS QUO SCENARIO

NOAA, along with other national and international organizations, spends substantial resources on maintaining and improving NWP weather forecast activities.

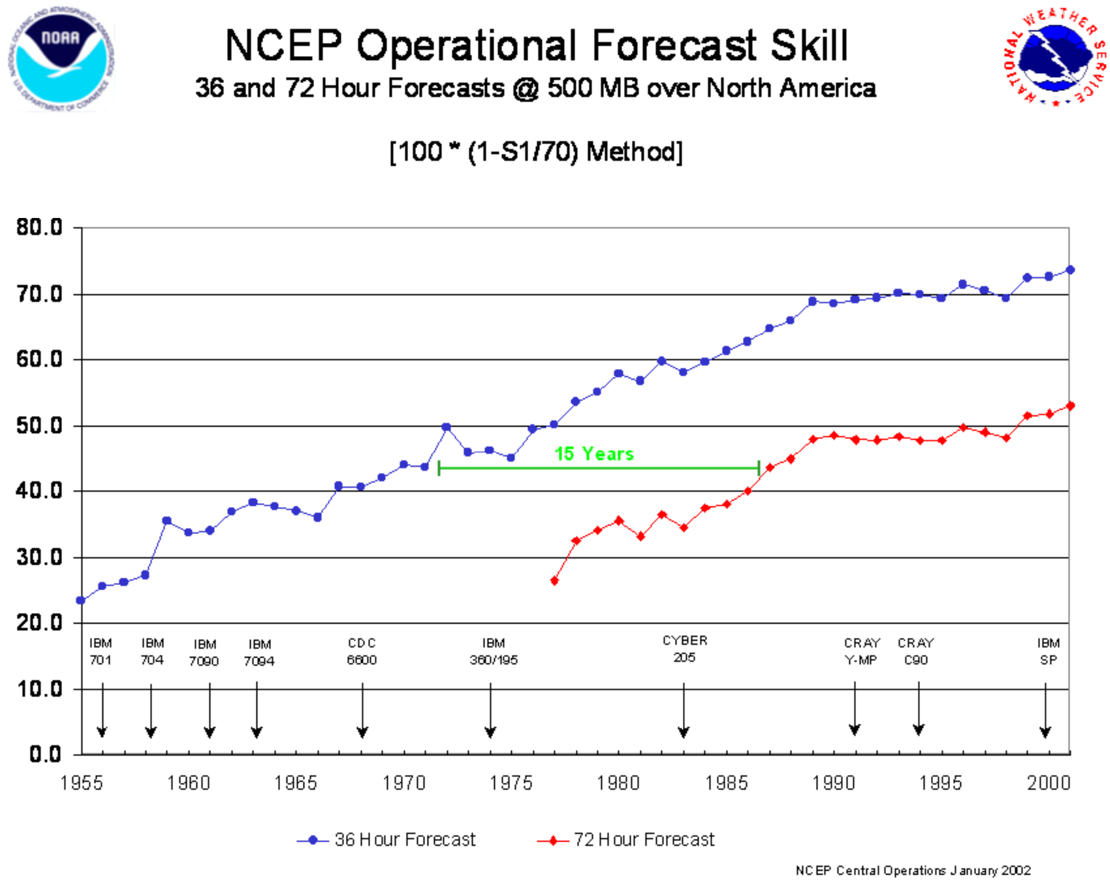

Fig. 3. S1-based skill of operational 36- and 72-hour lead time National Centers for Environmental Prediction (NCEP) 500 hPa geopotential height forecasts measured over the North American region between 1955 and 2001. Courtesy of NCEP Central Operations (NCO).

Due to these efforts, NWP procedures have shown a steady improvement over the past 50 years. For example, by 1990 the skill of a 72-hour forecast became as high as that of a 36-hour forecast made 15-18 years earlier (see Fig. 3).

However, in any learning situation, maintaining the rate of improvement becomes ever more difficult as the level of skill rises. Assuming no change in the level of research activities, one must realistically expect a decrease in the rate of forecast improvement. Not surprisingly, the rate of forecast improvement shown in Fig. 3 has decreased in recent years despite continued research efforts. Extrapolating the reduced rate of skill improvement observed since 1990 into the future, one might expect that without some major change in the forecast system, it would take around 46 years (more than twice the 18 years of the 1960-1990 period) for 72-hour forecasts to become as skillful as the current 36-hour forecasts. In view of ever increasing societal needs and expectations, such a decrease in the rate of forecast improvement, at a time when the sensitivity of society to weather and related water conditions is sharply increasing (see, e. g., Dutton 2002), may not be acceptable. The THORPEX program offers a new NWP strategy as an alternative to this status quo scenario.

2.3 THE THORPEX PROGRAM

THORPEX (2002) is a major international long-term Global Atmospheric Research Program coordinated in the US by the US Weather Research Program (USWRP). Currently eleven countries participate in THORPEX, which is under consideration for status as an official World Meteorological Organization (WMO) program.

2.3.1 THE NEW FORECAST PARADIGM

The motivation for THORPEX is the realization that accelerating, or even maintaining, the rate of forecast improvement requires a drastically new approach to numerical weather prediction. Therefore, THORPEX proposes to replace the old forecast system by one based on a new NWP paradigm. Under this new NWP paradigm, the forecast process is:

1) Integrated, with its interactive components developed as a whole;
2) Adaptive, adjusting to the evolving atmospheric environment;
3) Dynamically controllable by the users, adjusting to the changing user needs.

The major themes of the new NWP paradigm, and a research path to their development, are discussed in more detail in the next (Science Plan) section of this document.

2.3.2 SCIENCE OBJECTIVES

The main scientific goal of THORPEX is the development of an integrated, adaptive, and user controlled NWP forecast process. This new NWP process is expected to accelerate improvements in the accuracy and utility of operational global numerical weather prediction (NWP) forecasts that are of most interest to and have the largest impact on society. Due to its application-oriented nature, THORPEX has a great potential to significantly contribute to achieving the third Mission Goal of NOAA, serving “Society’s needs for weather and water information” (NOAA 2003), and maps directly onto the Strategic Goals of the US National Weather Service (NWS, 1999).

2.3.3 SERVICE APPLICATION GOALS

Considering other existing programs and activities, NOAA's primary interest in THORPEX is the development of scientifically based and cost effective new techniques that can *accelerate improvements in medium- and extended range (3-14 day) weather forecasts over the US*. Major improvements in weather forecasting techniques are expected to allow, for the first time, the issuance of

(1) Skillful probabilistic precipitation forecasts for the 3-7 day period;

(2) Skillful probabilistic daily weather forecasts for the 8-14 day period.

Accomplishing the second service goal will require advances in our knowledge of weather and climate processes, including the connections between the atmosphere and the ocean. Therefore addressing NOAA's second objective in THORPEX is also expected to lead to significant improvements in the area of climate monitoring and forecasting.

2.3.4 PROGRAM ORGANIZATION

2.3.4.1 Need for Collaboration

Science Objectives. The development of the new forecast paradigm and process requires a major investment in NWP-related research and development, spanning a wide range of disciplines from observing instrument and platform design through different branches of atmospheric sciences to economic and societal studies. Though isolated pieces of the proposed new forecast paradigm already exist today, the development of an integrated forecast process requires a comprehensive approach. To bridge the gap between the various components of the weather forecast process, research will be needed that cuts across the borders of the traditional disciplines. Given the wide range of disciplines and issues that need to be considered for the development of the necessary techniques, no single agency or nation on its own has the capability and resources to accomplish the overall scientific and wide-ranging service application goals of THORPEX. Interagency and international collaboration, proposed within the framework of THORPEX, is, therefore, a key element to success. Due to the application-oriented nature of the major THORPEX science goal, collaboration between the operational and research communities will also be essential.

Service Applications. Potential service applications also span a wide spectrum, from short- to medium- and extended-range weather prediction. No single agency or nation would be able to simultaneously develop viable applications in all of these areas. The different participating agencies and nations are expected to concentrate their work in application areas based on their particular priorities. By applying the same scientific principles, yet working on their specific application goals, participating agencies and nations can reap considerably more benefit from the international collaboration than their necessarily limited individual contributions to the program will be. By coordinating and leveraging efforts supported by various national and international organizations, the synergistic activities of THORPEX can lead to weather forecasting advances in all application areas that could not be achieved through the isolated work of individual agencies or nations. This unique, coordinated effort within THORPEX thus offers not only scientific advances from internationally coordinated research, but also the exchange of various service applications developed by the different organizations in the course of their THORPEX research.

Weather Forecast Research Program. While there have been a number of major national and international research programs aimed at improved monitoring and forecasting of climate since the First GARP (Global Atmospheric Research Program) Global Experiment (FGGE), no comprehensive program has been established to advance research in the area of *NWP weather prediction*. THORPEX is being organized, based on the recognition discussed above, that there is a great need for a major international program oriented at weather forecasting. Such a program, in coordination with the NOAA Office of Global Programs (OGP 2002) and international climate related research programs, such as the International Programme on Climate Variability and Predictability (CLIVAR) and the GEWEX (Global Energy and Water Cycle Experiment) Americas Prediction Project (GAPP), will significantly advance our weather forecast capabilities, and at the same time will help bridge the currently existing gap between short term weather and climate forecasting.

2.3.4.2 International and Regional Committees

The organizational structure of the international THORPEX program reflects the need for collaboration on a multitude of levels. The global scientific direction of the program is set by the International Science Steering Committee (ISSC), based on general guidelines from the International Core Steering Committee (ICSC). The ISSC considers the needs of the different regions, expressed by the Regional Science Steering Committees (RSSC) and their oversight bodies, the Regional Core Steering Committees (RCSC). The RSSCs and RCSCs in turn receive input from and coordinate the work of individual participating nations and agencies. While the International Committees have been formed, the Regional Committees are currently being organized (such as the Asian, European, and North American THORPEX committees (ASSC, ACSC, ESSC, ECSC, NASSC, NACSC)).

2.3.4.3 Extramural Contributions

Regional Efforts. European nations are likely to focus their attention on improving 1-3 day forecasts over Europe, while the Asian nations will likely center their THORPEX research on forecasting large impact atmospheric phenomena in their area of interest.

US Agencies. While NOAA is the major provider of NWP weather forecasts for civilian applications in the US, a variety of Department of Defense agencies such as the Air Force Weather Agency (AFWA), the Office of Naval Research (ONR), the Fleet Numerical Meteorology and Oceanography Center (FNMOC), and the Naval Research Laboratory (NRL) are also expected to benefit from THORPEX research. Meteorological sensors and observational network design are of particular importance to defense operations over data sparse regions. NRL in particular has a significant program in observational network design, data assimilation, and predictability, while the Office of Naval Research (ONR) will likely focus its THORPEX efforts on enhanced observing, data assimilation, and forecasting activities related to smaller spatial and time scales.

Among the other US agencies that have similarly strong interest in THORPEX, the National Aeronautics and Space Agency (NASA) is particularly interested in the validation of new types of satellite data against in-situ observations. Such an effort in the framework of THORPEX would allow a thorough testing of data in terms of state of the art data assimilation and forecast applications. For example, NASA's Langley Research Center took a leading role in organizing the first THORPEX Observing System Test (TOST) period, where a number of remote and in-situ observing platforms are deployed over the northeast Pacific in February-March 2003. This program coincides with the Winter Storm Reconnaissance (WSR, Toth et al. 2002) program of the National Weather Service (NWS), offering benefits to both the research-oriented TOST and the operational WSR programs. The Data Assimilation Office of the NASA Goddard Space and Flight Center (GSFC) and the multi-agency Joint Center for Satellite Data Assimilation (JCSDA) will be other important US players in the THORPEX program. While other agencies and nations may focus their interest on achieving specific forecast service goals, National Science Foundation (NSF) may direct most of its efforts to advancing the general science goals of THORPEX.

2.3.4.4 NOAA's Role

As a Beneficiary. The accomplishment of NOAA's THORPEX related service application goals (3-14 day probabilistic forecasts) are contingent upon fulfilling the overall THORPEX science objectives (integrated, adaptive, and user controlled forecast process), and eventually upon the success of the international program as a whole. Therefore all the extramural efforts described above will complement NOAA's work aimed at improving 3-14 day forecasts over the US.

Collaborative efforts are especially critical for achieving NOAA's THORPEX goal; the improvement of weather forecasts over the US on the longer, 3-14 day time scales.

The quality of such forecasts is affected by atmospheric, oceanic, and other types of observations (or the lack of them) over vast areas of the northern hemisphere, the tropics, and eventually the entire globe. Without intense international collaboration, the collection, assimilation, and further processing of critical new in-situ and remotely sensed data could not take place, impeding progress in NWP. In addition, NOAA is also expected to benefit from THORPEX collaboration by adapting forecast applications developed by other agencies and nations in the 1-3 day lead-time range.

As a Contributor. NOAA will contribute to the success of THORPEX primarily by advancing the general THORPEX science goals through its efforts in the 3-14 day forecast service application area. Scientific advances and new techniques in the four sub-areas of forecasting developed by or with the financial support of NOAA will be shared and actively distributed among other THORPEX participants and the broader weather forecast provider and user community both on the national and international level.

3. SCIENCE PLAN

The NOAA THORPEX Science Plan is centered on a number of basic science questions and hypotheses related to the four major components of weather forecasting. These questions are explored in a series of interrelated research and development tasks, including some especially critical tasks that cut across the traditional boundaries of the different components of the forecast process. A number of particular activities and methods to be developed by THORPEX are also discussed. Individual or group research initiatives funded through this Long-term NOAA THROPEX Research Program are expected to address different aspects of this Science Plan. The NOAA THORPEX Science Plan is consistent with the International THORPEX Science Plan (THORPEX 2001, 2002) where different aspects of the program are discussed in more detail.

3.1 MAJOR THEMES

The new approach to NWP-based weather forecasting proposed by THORPEX is based on three major themes:

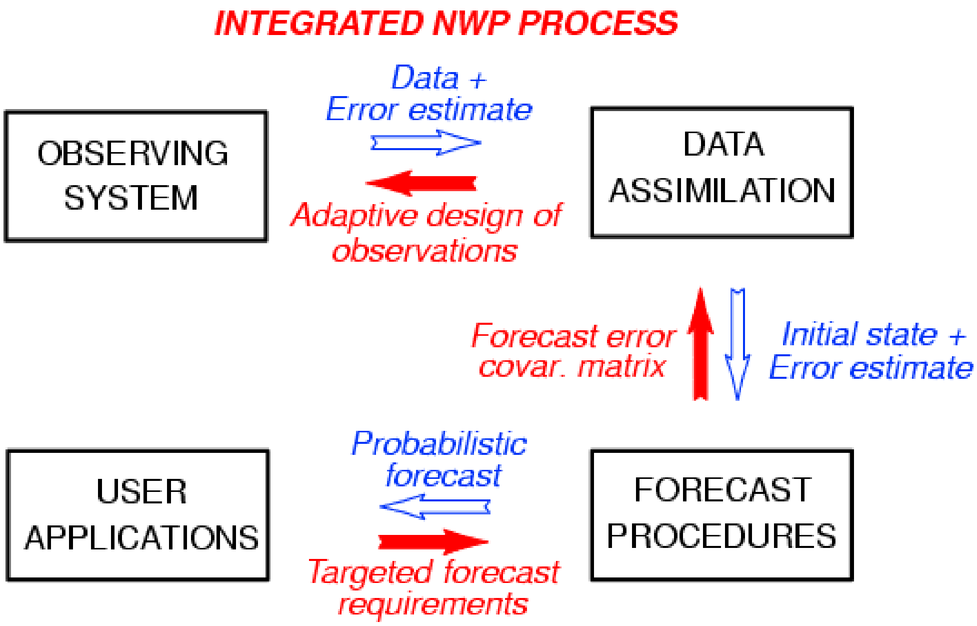

Fig. 4. Schematic diagram illustrating the two-way flow of initial condition related information in the proposed new, integrated NWP forecast process.

1) NWP forecasting must be considered as an end-to-end, *integrated* process. The four main components of NWP have to be considered as sub-systems of the forecast process that must be developed in concert. Accordingly, the old, one-way links between the various NWP components (Fig. 2) must be replaced by two-way interactions, facilitating the feedback of requirement-related information for the different components of the NWP process (see red arrows in Fig. 4).

As an example, let us consider the *uncertainty* contained in the output of an NWP sub-system that is passed to the next level for use as input. Such information can be critical for optimal forecast performance. For example, to ensure their optimal use in data assimilation algorithms, observations must be accompanied by estimates of random and systematic errors. Similarly, atmospheric analyses are not complete without an estimate of their error covariance matrix, for use in ensemble forecasting. Also, for enhanced utility, weather forecasts must be associated with their own case dependent error estimates, the most complete form of which is a set of probabilistic forecasts.

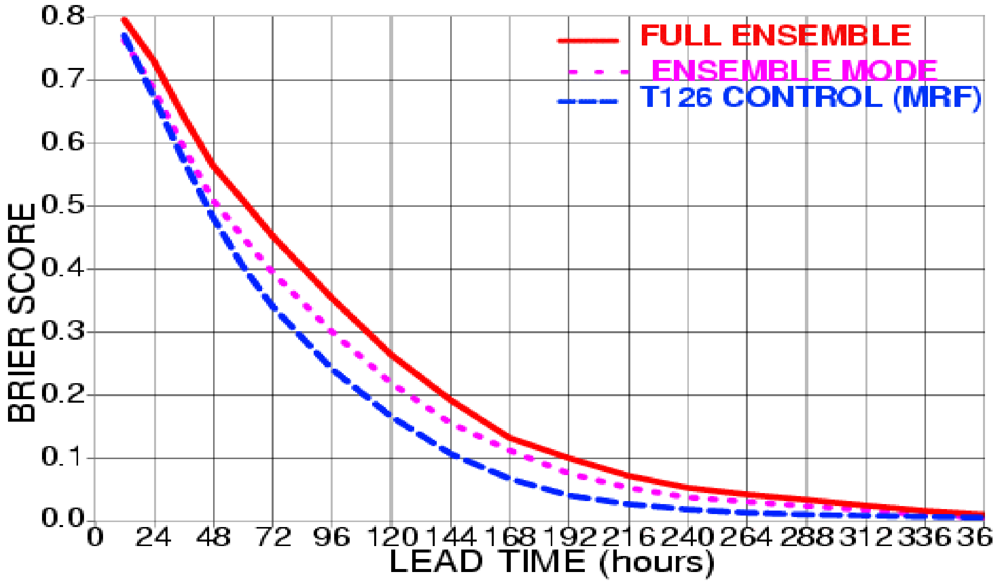

Fig. 5: Probabilistic verification scores (Brier Skill Score for extreme Northern Hemisphere extratropical 500 hPa geopotential height categories, averaged for March-May 1997) based on (a) a single control forecast with constant probability values (dashed blue, corresponding to yes and no forecasts), (b) the ensemble mode forecast (dotted purple, still only 2 probability values used but they vary based on the ensemble distribution), and (c) a detailed ensemble-based probability density distribution (solid red, with multiple probability values). Note that an 8-day detailed probability forecast has as much value as a bi-variate probability forecast at 6-day lead-time.

It is well known that uncertainty in weather forecasts can be critical in many real life applications (see Fig. 5, and, e. g., Zhu et al. 2002; Toth et al. 2002, and references therein). Lack of proper feedback between the different components of the NWP process means that information on the uncertainty in many of the intermediate (and also final) products has not been widely used in NWP forecasting. The THORPEX program will foster interdisciplinary research to explore and design the complex set of connections and feedback mechanisms among the different sub-systems in the NWP process. By identifying, then exploiting the sometimes hidden connections between the different components (like the need for communicating information on uncertainty), the functionality of the entire NWP process can be enhanced. The rigid, single-threaded input-output arrangement that characterizes current operations (see Fig. 2) can then be replaced by a web of two-way interacting links that connect the different components of the NWP process.

The first theme of the new NWP paradigm, the two-way interacting connections within an end-to-end NWP process, requires a careful, analytic study of the forecast process itself. The second theme of the new paradigm is based on a more detailed and thorough study of the natural processes that we try to predict in the atmosphere and its surrounding spheres:

2) The new, integrated NWP process is *adaptive* in nature. As our understanding of the natural processes matures, the procedures used in the different sub-systems of the NWP process can become more refined and differentiated. While under the traditional paradigm the same procedures are typically used irrespective of the situation, forecast techniques will be conditioned according to the state of the natural system, reflecting detailed and specific information on the flow.

Under the new NWP paradigm, for example, observations are collected in such a way that the gaps that would occur at various places, depending on the flow configuration under a climatologically fixed observing network, would be filled in a flexible manner by the use of adaptive observing platforms. When the observational and short-range forecast information is merged in data assimilation, the error in the forecast component is estimated in a flow dependent, adaptive manner, potentially reducing overall analysis errors. NWP modeling and ensemble schemes can also be improved by allowing them to adaptively shift resources or change procedures as the forecast situation dictates. As for the last NWP sub-system, the availability of probabilistic forecast information will allow the users, for the first time, to fully adapt their application procedures to the expected weather situation.

Finally, according to the third major theme of the new NWP paradigm:

3) The new NWP process, to be developed and introduced by THORPEX, should be *dynamically controllable to satisfy a set of user requirements*. User control of the forecast process becomes feasible when the first two themes of the new NWP paradigm are combined. The integration of the forecast process (first theme) is envisioned here not in a climatologically optimized, or somewhat rigid form, but rather in an adaptive fashion where all the elements of the forecast process are determined with respect to by the evolving atmospheric flow (second theme), and are driven by and responsive to the continually changing needs and requirements of the end users (third theme).

Development of the third theme of the new NWP paradigm will allow the users to interact with the data collection, data assimilation, and forecasting components of the NWP process, in accordance with the natural dynamical processes. (User interests here refer to the collective needs of the user community. How to articulate such interests is one subject of the Applications sub-program, discussed below.) Depending on user priorities and needs, special observations can be collected or specific forecast procedures can be invoked to improve certain aspects of weather forecasts. Along with the adaptive procedures outlined above, such a direct user feedback onto the forecast process is one of the central elements of the new, dynamically controlled, adaptive, and integrated approach to NWP forecasting.

The user control of the forecast process is achieved through an understanding of the natural processes that are being forecast on one hand, and of the integrated forecast process on the other. Consequently, most user control mechanisms will exploit the dynamical NWP modeling and ensemble forecasting tools that can connect the users with the other, observational and data assimilation sub-systems of the interactive forecast process. Note that the same modeling and ensemble tools also provide the best representation of the dynamics of the atmosphere and the surrounding spheres.

In recent years, some elements of the new NWP process have already been developed. A good example of recent efforts aimed at the integration of the different NWS sub-systems is the multidisciplinary research used in the Department of Commece (DOC)/DOD/NASA joint National Polar-orbiting Operational Environmental Satellite System (NPOESS, 2002), under the direction of the Integrated Program Office (IPO). When developing the next generation polar orbiting satellite system, NWP and other user requirements (not just the traditional instrument and platform constraints) are also considered as an integral part of the planning process.

Examples of adaptive NWP forecast elements include the event-driven use of forecast procedures at the NWS, including the operational use of a hurricane forecast NWP model (Kurihara 1998). A recently introduced operational program, the Winter Storm Reconnaissance (WSR, Toth et al. 2002) program, serves as a good example for the use of the concept of dynamical control in the NWP process. This program was developed based on research carried out in the former FASTEX (Joly et al. 1999) and NORPEX (Langland et al. 1999) research programs, and is guided by the feedback users - in this case, synoptic forecasters - provide to the NWP forecast process. During WSR programs, operational NWS forecasters request the collection of extra observations to reduce forecast errors for selected high impact winter storms. Dropsonde observations are then taken based on dynamical considerations, in areas deemed optimal for improving the selected aspect of the weather forecast. Verification results indicate that the skill of 36-96 hour targeted forecasts is as high as 12-hour shorter, 24-84 hour forecasts without the benefit of the targeted observations (see Fig. 6).

Based on these early trials, THORPEX will strive to make interactive, adaptive, and dynamically controlled procedures the norm (and not the exception) in the NWP process. Based on a more thorough and detailed understanding of natural processes, and an in-depth analysis of observing, data assimilation, forecasting, and application procedures, the forecast process will be formulated to adapt to the changing natural environment on one hand, and to the varying user requirements on the other. This will bring NWP forecasting to a level never reached before, significantly improving existing, and opening the possibility for the introduction of many new societal and economic applications.

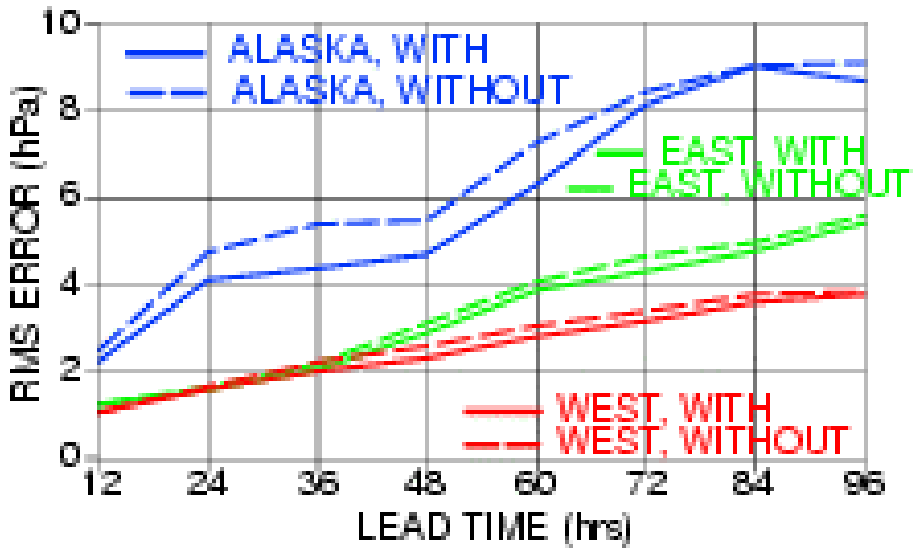

Fig. 6: RMS error of surface pressure forecasts with (continuous lines) and without (dashed lines) dropsonde data for the 12 observational cases in the Winter Storm Reconnaissance 2000 program, verifying over the West coast (25-50N, 125-100W), Eastern US (25-50N, 100-70W), and Alaska (55-70N, 165-140W). From Toth et al. (2001).

3.2 OPEN SCIENCE QUESTIONS

One is confronted by a number of basic scientific questions along the road to the development of the proposed new paradigm describing an integrated, adaptive, and dynamically controlled NWP process. THORPEX research must address these questions before NOAA's THORPEX related service goal, accelerating forecast improvements in the 3-14 day lead-time range, can be achieved and the full potential of weather forecasting realized.

OBSERVING SYSTEM

1) On the most basic level, one would like to know what combinations of observable atmospheric variables, at what temporal and spatial resolution, and with what observational error level, can lead to high quality NWP analysis fields. Also, will the quality of analysis fields improve more with an increase in the number of observed variables, with an improvement in observation quality, or with higher spatial or temporal resolution for observations?

These questions, as the other observation-related science questions that follow, can be answered only in the context of the full NWP forecast process, and so will require collaboration with data assimilation and forecast applications. Given some theoretical understanding of how to enhance forecast quality with changes in the number of observed variables, their error level and spatio-temporal resolution, the following question arises:

2) What is the optimal (most cost-effective) mix of existing or planned remote (ground-, aircraft-, or satellite-based) and in-situ platforms and instruments that can provide the most cost-effective approach in obtaining the requisite combination of observations in the framework of the global observing system?

This question, of course, should be addressed in the context of our new, integrated NWP paradigm, which leads to the following, even more practical question:

3) What modifications/developments in observing platforms, instruments, and techniques can make the observing system more flexible and adaptive, responding to the needs of a dynamically interactive NWP forecast process?

Finally, the expected abundance of remotely sensed data and recent advances in on-board and receiving station data processing speed and quality point to another question:

4) For increased efficiency, what part(s) of the data selection, super-obing, retrieving, or other types of data analysis procedures, if any, should be carried out prior to and independent of the next step in the forecast process, NWP-based data assimilation?

One may argue that from a scientific point of view, these tasks should be considered as part of the data assimilation procedure and carried out within, not outside, that framework. It is not clear, however, how much information is lost by performing some tasks prior to the NWP data assimilation procedure that, for example, can result in a dramatic reduction in data volume. The reduced data load may free up resources within the data assimilation procedure that can possibly be used more efficiently to improve other aspects of data assimilation. It is obvious that answering this last question requires the most intimate working relationship between observing system and data assimilation experts, thus providing a prime example for the interdisciplinary research promoted by THORPEX.

DATA ASSIMILATION

As pointed out above, from an NWP perspective observing systems and data assimilation procedures cannot be discussed independently. In fact, the first scientific question raised in the context of data assimilation procedures is closely related to the last question raised under observing systems:

1) What existing or new procedures can be used to ensure that information from the large amounts of remotely sensed, primarily space-based observations are optimally used in data assimilation?

Given the projected increase in data volume, the proper handling of this issue is of paramount interest. The second critical element in the integrated NWP process, from a data assimilation perspective, pertains to observing network design:

2) Given the technological and financial constraints, how can the global observing network be optimally configured? What is the ideal arrangement(s) of the routine (fixed) network? How large a role should adaptive observations play in the global observing network? Can adaptive observing techniques contribute to climate monitoring efforts? And what are the best adaptive observing techniques?

These questions are again closely linked with the issues listed under the Observing system sub-area. In particular, they represent the other, data assimilation side of the issues raised under questions 2 and 3 in the Observing system section. The last major data assimilation related issue is, relatively speaking, the most self-contained since it pertains to improved analysis procedures:

3) What are the best ways to enhance the data assimilation procedures? Is it more important to better describe the initial-value, or the model related errors in the assimilation schemes? Data assimilation procedures are the most relevant for systems that are under-observed. Given the expected robust increase in both the quality and quantity of remotely sensed data, what will be the future significance of enhancements in data assimilation schemes for the atmosphere?

FORECAST PROCEDURES

In the NWP process the collection and assimilation of data serve the ultimate goal of projecting the current state of the atmosphere into the future. NWP models, using an approximate numerical representation of the relevant dynamical and physical processes, are the major if not sole provider of information on which weather forecasts out to 14 days are based. It is well understood that due to its chaotic nature, the atmosphere has limited predictability. The limited skill of weather forecasts is an everyday reminder of this fact. Several critical aspects of limited atmospheric predictability, however, is not well understood. In particular:

1) What is the critical limiting factor in NWP weather forecasting: the lack of adequate observational coverage, inadequate data assimilation techniques, or

the use of imperfect models? Are non-modal processes important in forecast error growth? Depending on the nature, spatial scale, and location of the phenomena considered, how can weather forecasts be most easily improved: through collecting more/better observations, assimilating the existing data better, or developing and using more accurate models?

These are fundamental questions in weather forecasting that can be answered only through close collaboration with scientists working in the observing system and data assimilation areas of NWP. The answers to these questions may have important implications regarding the distribution of research and operational resources between the observing, data assimilation, and forecast areas of the NWP process. While limitations in the quality of weather forecasts due to observations and data assimilation are handled in those parts of the NWP process, forecast errors due to the forecast procedures themselves are the prime target of the forecast component of the THORPEX NWP research:

2) What are the sources of model-related errors in NWP forecasting? How, where, and in connection with what phenomena do the errors manifest themselves? What techniques can be used to reduce these errors?

Currently relatively little is known about model-related errors. To a large extent, this is due to the difficulty in identifying and separating model errors from initial value related errors. In chaotic systems, errors due to these two sources are necessarily intertwined and difficult to separate (see, e. g., Vannitsem and Toth 2002; Palmer 2001; Toth and Vannitsem 2002). In the NWP process the situation in the data assimilation procedure gets even more complicated by the use of short-range forecasts, which are generated by the same imperfect model as that used for other forecast applications. The use of the same NWP model in data assimilation explains why there is also a strong interest on the part of the data assimilation community in learning more about model-related errors. More, better organized, and more systematic information about model errors will obviously contribute to the development of new modeling techniques for the *reduction* of such errors. However, model errors, just like initial errors, are *unavoidable*. Therefore, based on some basic knowledge about the nature of model errors, one must go further and ask some more practical, yet critical questions:

3) Can variations in model related forecast errors be captured in ensemble forecasting? Can the forecast model be enhanced in such a manner that when run in an ensemble mode, it could account for model related uncertainty?

Such an *inclusion* of uncertainty in weather forecasting may first sound counterproductive, especially to modelers who aim above all at high accuracy. Research in ensemble forecasting, however, has demonstrated that the inclusion of uncertainty related to the initial value can enhance the potential economic value of weather forecasts (see, e. g., Richardson 2000; Zhu et al. 2002). The proper inclusion of model-related uncertainty in ensembles could, therefore, be a major untapped forecast resource waiting to be realized by THORPEX research, potentially leading to enhanced probabilistic forecast information.

The extent that a priori, ensemble-based knowledge about case dependent model errors can enhance the economic value of weather forecasts is one of the unknowns that can be explored only through close collaboration with scientists working in the societal and economic applications area of NWP forecasting.

SOCIETAL AND ECONOMIC APPLICATIONS

Forecast applications represent a link between information on future weather and the users of this information. This last step in the integrated NWP forecast process is often neglected, or treated independently from the rest of the process. To the extent that the quality of weather forecasts can be measured and to a certain level, also improved without respect to its use by society, such a treatment may be justified. But there are some unique benefits, attainable only by considering the generation and the application sides of the NWP process together:

1) How can the utility of weather forecasts be enhanced beyond that attainable by improvements measurable in terms of quantitative NWP forecast skill? What meteorological information is needed, and how this information can optimally be post-processed and used for maximizing the utility of weather forecasts?

Though these basic questions can be raised only by considering both the generation and application sides of NWP, they can be addressed without much consideration of the new paradigm of an integrated NWP process. To realize the full potential of NWP, however, one has to develop critical links between applications and the other NWP forecast components.

Under the new NWP paradigm, users are no longer just passive receivers of information on future weather. Considering the socio-economical implications of the forecasts, they can request that certain aspects of the forecasts be adaptively enhanced, depending on the associated costs. Such enhancements can be attempted through the introduction of special data collection, data assimilation, or forecast procedures, aimed at benefiting a specific forecast application while making a neutral or slightly positive overall impact on general forecast quality. Related questions that arise are:

2) What procedures need to be developed so that users can efficiently interact with and enhance the integrated NWP forecast process? What arrangements can guarantee that users have equitable access to available forecast resources? What is the most cost-effective way of improving selected aspects of weather forecasts: by

taking extra, adaptively placed observations or by introducing special data assimilation and/or forecast procedures, such as the generation of higher resolution or more ensemble forecast members? How can the economic and societal benefits be quantified?

Given that these questions cut across several disciplines in the natural and societal sciences, answering these questions is a rather complex task, even for individual users or a group of users. To generalize information developed on individual users' costs and benefits is an even more challenging task:

3) What new informational, scientific or other techniques are needed to estimate the overall societal costs and benefits associated with the introduction of different versions of the new, integrated, adaptive, and dynamically controlled NWP forecast process proposed by THORPEX?

If such techniques can be developed then THORPEX will be in a position to answer the penultimate question:

4) Given the overall costs and benefits associated with the different versions of the new, integrated NWP process, which, if any, of the proposed new observational, data assimilation, forecast, and application procedures are (most) cost effective for global NWP forecast applications in the 3-14 day lead time range?

The proposed new NWP process, as pointed out earlier, is not a linear sequence of activities but rather an interactive loop. Answering the last question will close this loop from a development perspective. The answer will determine whether the proposed new methods are cost effective, and if so, which version of them should be operationally implemented.

3.3 RESEARCH AND DEVELOPMENT TASKS

Note that it may not be possible to find definitive answers to some of the open scientific questions; and some of the answers may depend on current methods and techniques. Focusing on and continually revisiting these science questions, however, is expected to significantly enhance the knowledge base of NWP forecasting. To address the scientific questions (SQ) raised above, a wide range of studies needs to be completed in each NWP sub-program. These studies form a series of research activities, often interconnected with those undertaken in other sub-programs, with the aim of developing and constructing the methods and techniques that constitute the critical new elements of the integrated, adaptive, and user controlled NWP process.

While the activities aimed at the development of the various methods and components of the new NWP process are listed below, under the four separate sub-areas of NWP, it is important to note that each of them will have to be carried out in the context of the integrated NWP process, possibly in collaboration with other sub-programs. To foster such collaboration and to ensure that the different newly developed components can be naturally integrated, the research efforts in the sub-areas of the new NWP process will be complemented by a series of cross-cutting activities. When particular research efforts are focused in time, the most active time frame is indicated in terms of short (1-4 years, ST), medium (5-7 years, MT), or long term (8-11 years, LT) periods. When such a period is not specified the activity is expected to be carried out on a continual basis throughout the life of the program.

OBSERVING SYSTEM

1) Develop new in-situ and remote sensing instruments and platforms that can best complement or fill any gaps in the current observing system, regarding NOAA's THORPEX goal of improved 3-14 day forecasts over the US. Evaluate new elements in the field in THORPEX Observing System Tests (TOST) (SQ #2, ST-MT)

2) Develop intelligent sensor arrays (Steiner et al. 2003), observing techniques, and instrument platforms to be used in a dynamically controlled, adaptive fashion. Evaluate new elements in the field during THORPEX Observing System Tests (TOST) (SQ #3, ST-MT)

3) Improve techniques for processing extensive sets of remotely sensed data (SQ #4).

   (a) Refine existing methods, and develop new methods for:

      (i) Combining remotely sensed and in-situ observations (calibration);
      (ii) Deriving meteorologically relevant but directly not observed quantities;
      (iii) Collapsing the vast amounts of observations, with minimal information loss, to a more manageable size (thinning or "super-obing");

   Joint research with Data Assimilation sub-program:

   (b) Evaluate which of the above procedures are best applied prior to (on observing platforms or at ground data processing centers), or within the NWP data assimilation process, considering the final quality of NWP analysis products and also data transmission, processing, and other costs.

(c) Estimate (both correlated and uncorrelated) errors in raw observations and derived products

Joint research with JCSDA:

(d) Prepare in advance for planned new satellite-based observations before launch for readiness upon acquisition. Evaluate new strategies(see points a-c above) in the field during THORPEX Observing System Tests (TOST).

4) Upgrade current meteorological data communication technologies. Develop and maintain a joint observations/forecast database that can serve the various needs of the THORPEX research community (Core activity, to facilitate efficient research and subsequent operational implementation)

DATA ASSIMILATION

1) Improve techniques for the use of new and existing types of observations in NWP data assimilation techniques (SQ #1).

a) Refine existing, and develop new techniques for the use of large amounts of remotely sensed data, including

(i) Forward models;
(ii) Sophisticated algorithms for the retrieval of state variables at high resolution;
(iii) Thinning, “super-obing”, or merging of data;
(iv) Approximate treatment of data (such as fast radiative transfer codes or retrievals);
(v) Treatment of observations with correlated error.

Joint research with Observing System sub-program:

b) Considering data transmission, processing, and other costs,

i. Evaluate which of the above procedures are best applied prior to (on observing platforms or at ground data processing centers), or within the NWP data assimilation process.
ii. Compare the value in assimilating high resolution state variables or traditional bulk radiances.

c) Foster related research activities with appropriate research facilities such as the Cooperative Institute in Meteorological Satellite Studies (CIMSS), Cooperative Institute for Research in the Atmosphere (CIRA), etc.

d) Assess errors in observations (instruments), representativeness, and forward modeling. Characterize the spatial and temporal correlations and flow dependence of such errors.

e) Develop techniques for the use of observational and other types of error information in advanced quality control and data assimilation procedures.

2) Develop and test sophisticated data assimilation schemes capable of using case dependent error covariance information (SQ #3).

a) Develop techniques to evaluate the quality of background error covariance information in a probabilistic fashion. Assess the importance of forecast error covariance information in 4DVAR data assimilation procedures and develop techniques for its continual update.

b) Evaluate the strengths and weaknesses of various ensemble based data assimilation schemes. Develop fast, parallel computational algorithms for the update step of ensemble-based data assimilation schemes.

Joint work with Forecasting sub-program:

c) Refine ensemble perturbation techniques to best account for errors in the initial value-related uncertainty.

d) Explore the effects of data assimilation applications in the presence of model error, and develop new assimilation methods applicable in such an environment.

3) Investigate adaptive observing strategies (SQ #2).

a) Explore the use of fast analysis procedures in the local use of high density adaptive observations;

b) Develop adaptive observation techniques applicable in the presence of

i) Strong non-linearities affecting, for example, synoptic scale motions in the medium range, or physical processes (moist convection, turbulence) in the short range;

ii) Model errors;

c) Assess the effectiveness of various adaptive observing techniques in predicting the impact of (supplementary) observations on the quality of analysis and forecast products;

d) Assist the broader research community in assessing the impact of the use of adaptive observations on nowcasting, climate monitoring, and other non-NWP activities.

FORECAST PROCEDURES

1) Evaluate the relevance of non-modal processes in the growth of forecast errors (SQ #1, ST-MT).

Joint work with Data Assimilation sub-program:

Refine ensemble perturbation techniques to best account for errors in initial value related uncertainty.

2) Develop and refine methods for separating model-related forecast error from initial value related errors. Analyze to what extent model errors exhibit stochastic or systematic behavior. On different spatial and temporal time scales, identify what atmospheric features/phenomena are affected most by model-related errors or drift (SQ #2, ST-MT);

3) Assess what critical model features/processes are responsible for generating model-related errors (SQ #3);

   a) Improve the formulation of NWP models, including techniques used to couple different model domains and components, to reduce model related errors;
   b) Develop techniques to explicitly account for model-related forecast uncertainty in ensemble forecasting;
   c) Assess the applicability of adaptive procedures in NWP modeling and ensemble techniques.

SOCIETAL AND ECONOMIC APPLICATIONS

1) Given the interdisciplinary and relatively less developed nature of the application component of NWP forecasting, convene a workshop to discuss methods for assessing the costs and benefits associated with NWP forecast procedures (SQ#2,3, ST, core activity to foster societal applications-oriented NWP research in general.)

2) Refine existing methods, and develop new and more efficient methods for the use of NWP forecasts (SQ #1, ST-MT).
   a) Improve statistical forecast post-processing techniques to reduce systematic forecast errors;
   b) Explore what new meteorological information could potentially enhance forecast utility;
   c) Develop methods for the application of new, probabilistic forecast information by intermediate (human forecasters) and end users.

3) Develop methods for the evaluation of costs associated with different aspects of the NWP forecast system, including those shared by various users (e. g., satellite observations) (SQ #3, ST-MT).

Joint research with the other sub-programs:

Assess the costs associated with the potential introduction of the new observing, data assimilation, and forecast procedures proposed by THORPEX.

4) Adapt existing, and develop new techniques for estimating the societal/economic benefits of improved NWP forecasts for individual users, sectors of the economy, and the society as a whole (SQ #3, ST-MT). Based on the results, assess the feasibility of developing new NWP verification measures that may better reflect the societal value of forecasts.

5) Study the societal aspects of adaptive NWP procedures, such as targeted observations and data assimilation and forecast applications tailored to specific applications (SQ #2, MT-LT). Develop guidelines and procedures that ensure the equitable use of NWP resources.

CROSS-CUTTING TASKS

The new methods developed above are merely building blocks for, not the end product of the new NWP paradigm. The newly developed methods need to be integrated and tested in the end-to-end forecast process, requiring the collaborative work of all four sub-programs. The following synergistic activities are required for the full development, testing, and subsequent operational implementation of the new NWP forecast process.

1) Evaluate the data needs of the NWP forecast process for the 3-14 day lead time range using, for example, idealized Observing System Simulation Experiments (OSSEs, see, e. g., Atlas 1997) (Observing System SQ #1, ST). Study the trade-off between observing more variables, vs. at higher spatial or temporal resolution, vs. with lower observational error for forecast applications on different time and spatial scales.

These idealized and platform neutral experiments aim at establishing the basic data needs of NWP forecasting. After learning what variables, and at what resolution are the most important for NWP forecasting, THORPEX can look into the next question: how can these observations be collected?

2) In the framework of OSSE experiments, evaluate the value of existing and proposed new in-situ and remote components of the observing system in providing the observational information required for 3-14 day NWP applications (Observing System SQ #2, ST-MT). Propose observing system configurations that can satisfy the ideal needs of NWP forecasting at a minimum cost. Assess

the value of adaptive observing techniques in achieving these goals (Data Assimilation SQ #2).

Once the basic elements of the observing system are optimized, its contribution relative to the other components of the NWP process can also be quantified:

3) In the framework of OSSE experiments, evaluate the relative value of improvements in the observing system, data assimilation procedures, vs. numerical modeling and ensemble techniques, with the goal of optimizing the use of overall resources for the 3-14 day lead time range (Forecasting Procedures SQ #1, MT).

The identification of the most critical limiting factors in NWP forecasting will allow for a rational allocation of NWP resources for both research and operational implementation purposes:

4) Based on the methods and techniques developed in the research activities of the four sub-programs (see previous subsections), and on the results of the cross-cutting activities discussed above, develop a small number of configurations for the new, interactive NWP forecast system. In a realistic forecast environment, test one or two of the integrated global NWP system candidates that performed best in OSSE experiments. If necessary, carry out a major field program to demonstrate the feasibility and value of the new observing, data assimilation, forecasting, and application procedures in the 3-14 day lead time range (Societal and Economic Applications SQ #4, MT-LT).

The related NOAA research activities will culminate with a recommendation for the configuration of the most cost effective, new, integrated, adaptive NWP process, to be introduced operationally at the end of the THORPEX program.

4. IMPLEMENTATION PLAN

4.1 PROGRAM ORGANIZATION

4.1.1 PROGRAM ADMINISTRATION

The overall direction of NOAA's THORPEX program is set by the NOAA THORPEX Executive Oversight Committee (NTEOC), which also makes all related budgetary decisions. The NTEOC is co-chaired by the Director of the Office of Oceanic and Atmospheric Research (OAR) Office of Weather and Air Quality (OWAQ) and the Director of NCEP, and also includes the Directors of the National Environmental Satellite, Data, and Information Service (NESDIS) Office of Research and Applications

(ORA), and the NWS Office of Science and Technology (OST).

The wide-ranging activities discussed in Sections 3 and 4 are coordinated on a daily basis by the Leader of NOAA's THORPEX Research Program, who is appointed by and reports to the NTEOC. He/she is assisted by the NOAA THORPEX Science and Implementation Team (NTSIT), that he/she forms from NOAA and extramural scientists specializing in the four major components of the forecast process. This team, with input from interested NOAA line offices and the wider community, is responsible for developing and continuously updating the NOAA THORPEX Research Program Plan, including its Science and Implementation components, as well as overseeing the execution of the program. This includes administration of NOAA's THORPEX research grant program, establishment of the necessary infrastructu (core activities), coordination of supporting research and development work within NOAA, and collaboration with extramural THORPEX (and other research) program activities on the national and international level. Several members of the NTSIT, including its leader, are expected to serve on the NASSC and the ISSC to ensure that the activities carried out at the different levels of the THORPEX program are well coordinated.

4.1.2 EXTRAMURAL RESEARCH GRANT PROGRAM

More than half of all NOAA THORPEX funding will be used to support research initiatives developed and carried out by extramural scientists in response to NOAA THORPEX Announcements of Opportunities (AO). Research proposals will first be peer reviewed through mail, then prioritized by a panel including NTSIT members, according to their ability to contribute to NOAA's THORPEX science and service related goals. Proposals for research that cuts across the traditional boundaries between the different components of NWP, and proposals submitted jointly by experts from different sub-areas will be especially encouraged.

Research proposals will be evaluated based on the following three (weighted) criteria:

1) **Scientific merit**, including both the potential to advance a given topic and to fit with related activities within THORPEX (40%);
2) **Relevance to the NOAA THORPEX science and service goals**. Ability to demonstrate how the research results will lead to improved forecast skill or will support other activities achieving that goal. A credible path to operational implementation is considered an important part of each research proposal (40%);
3) **Preparedness of the investigators** (scientific background and productivity) and the availability of adequate facilities to carry out the research, including potential partnership with operational centers, other research groups, or the user community if necessary, and educational potential (20%).

To increase efficiency and decrease costs, funding for field experiments will be considered only if the applicants carefully explore other uses of the data to be collected, and seek partial funding from sources outside the NOAA THORPEX program; or it is clearly demonstrated that the need for the data is unique and essential to achieving NOAA's THORPEX goals.

4.1.3 INTRAMURAL RESEARCH PROGRAMS

NOAA's THORPEX program builds on a rich web of scientific and development activities that have been carried out at different NOAA line offices. The offices with considerable expertise and interest in the four sub-areas of THORPEX research include:

1) The Environmental Modeling Center (EMC) of the National Centers for Environmental Prediction (NCEP), where the operational NWP data assimilation and forecasting procedures are being developed, prepared, and maintained for operational use;
2) The Climate Diagnostics Center (CDC), where research projects in the areas of NWP data assimilation, forecasting, and application are carried out;
3) The Environmental Research Laboratory (ERL), where new observing system applications are being developed;
4) The Forecast System Laboratory (FSL), where new forecast systems are developed;
5) The Office of Global Programs (OGP), where among many other activities, societal applications of environmental forecasts are considered on an international basis.

These in-house activities within NOAA should be coordinated with the THORPEX program. An incremental enhancement of some of these programs will allow the NOAA Labs to act as portals for extramural research initiatives wishing to connect with NOAA research and operational activities. Examples include the development of specialized real time or near real time products, such as forecasts, forecast sensitivity, or data impact fields used in the execution and evaluation of field experiments, and standard verification software to be used in conducting and evaluating NWP forecast research experiments (OSSE). Such arrangements can significantly enhance the success of the THORPEX program.

As the extramural research proposals, all internal funding initiatives will be peer-reviewed and if funded, their progress re-evaluated on a regular basis. In the review process, the same criteria will be used as described in Section 4.1.3 for the extramural grant program except the relative weights for the criteria will change (1 – 20%, 2- 30%, 3 – 20%), and they will be supplemented by a new criterion:

4) **Ability to promote collaboration.** The potential of the proposed work to conduce new extramural research efforts, to foster collaboration between NOAA and

extramural research efforts, and to facilitate interactions between research and operational activities.

4.1.4 INFRASTRUCTURE / CORE ACTIVITIES

Many of the THORPEX research and development activities envisaged by NOAA or other agencies will require or greatly benefit from some core activities. The NOAA THORPEX Program intends to contribute funding to the following critical organizational and infrastructural activities, for the benefit of NOAA's and the wider community's THORPEX related efforts (emphasis in time, when significant, indicated in parentheses):

1) Continual upgrades of the communication capabilities to allow the exchange of large amounts of data. Neither the research nor the operational work envisaged by THORPEX will succeed without the ability to move large amounts of observational and NWP modeling data from their sources to the research and operational users, including stops at centers for intermediate processing.

2) Establishment of a THORPEX database, containing all observational and forecast data of possible value to the general THORPEX research community (ST). Without such a facility THORPEX efforts would necessarily be fragmented and sub-optimal.

3) Establishment (ST), and maintenance (MT-LT) of an operational test-bed facility to provide institutional support for closer interaction between research and operational activities. Academic researchers should have access to a formal procedure to test their methods in a fully operational environment. The lack of such facilities has been noted in several prior reports (see, e. g., National Research Council, NRC 2000; Science and Technology Infusion Plan, STIP 2003) as a major impediment to advances in NWP science and technology. Therefore, the establishment of an Operational NWP Test Facility (ONTF), preferably co-located with the operational NOAA NWP center (NCEP), is a critical requirement. Such a center can act as a melting pot for the new ideas and procedures developed in the course of THORPEX and other research programs. Also, an NWP test-bed can be an ideal venue for carrying out the bulk of the cross-cutting THORPEX activities.

4) Real-time testing and demonstration of THORPEX forecast procedures. After they have been thoroughly tested in OSSE and other appropriate experiments, new observing, data assimilation, forecasting, and application procedures will undergo comprehensive, real-life tests. In the development phase of the

program, these tests will be carried out as part of various TOST experiments. In the last phase of the THORPEX program, it may be desirable to carry out a major demonstration of the integrated forecast process that THORPEX considers cost-effective and ready for implementation. Ideally, such a demonstration project can take place as part of the transition of the scientific results from a research into an operational environment, on an international basis near the end of the THORPEX program.

5) Organization of workshops and other meetings (ST). The exchange of ideas among the various research groups will be facilitated through workshops and other means. Such activities proved to be a catalyst in earlier research programs (e. g., FASTEX, see Joly et al. 1999; and NORPEX, see Langland et al. 1999). This will be especially important for new and cross-cutting activities, and during the early stages of the program.

4.1.5 COORDINATION WITH OTHER PROGRAMS / ORGANIZATIONS

Collaboration within the THORPEX program. NOAA's THORPEX Research Program will be fully coordinated with that of other agencies at the USWRP, North American, and international level. Since THORPEX results will be shared among all interested parties, science advances at any of the participating agencies will be incorporated into efforts of other agencies, including NOAA. NOAA's main focus in THORPEX service applications is on the 3-14 day precipitation and daily weather forecasts. NOAA will offer its own achievements in this area to other participants, and will take full advantage of different service applications developed by other participating agencies and nations.

Collaboration with other programs – Contributions. THORPEX will act as a catalyst for NWP forecast related activities with respect to a number of other atmospheric science programs organized under the USWRP (2002) or elsewhere (e. g., International H2O Project, IHOP; Pacific Landfall Jets Experiment, PACJET, Cold Season Precipitation Program, CSPP, etc, see Table 1). THORPEX will bring a wealth of NWP-related information and expertise that will enrich the other programs for the benefit of the user community.

PROGRAM/ ORGANIZATION	TIME PERIOD	NATURE OF INTERACTION	BENEFITS	CONTRIBUTIONS
CEOP/GAPP	2001-2004	Water and energy cycles	Observations, climate modeling	NWP procedures
CLIVAR	Continual	Climate variability	Observations,	NWP procedures

			climate modeling	
CSID/OGP	Continual	Societal impact	Methods, studies	Weather-climate connections
CPU PROVIDERS	Continual	Grid computing	On demand CPU	Potential customer
CSP/USWRP	2003-	Mesoscale processes	Observations, mesoscale NWP	Influence of large scale circulation
EARTH SIMULATOR CTR	Continual	High performance computations	Cutting edge simulations	NWP know-how transfer
IHOP	2002	Convective processes	Parameterization	Influence of large scale motions
IRI	Continual	International forecast services	Organization, societal impact	Weather forecast connection
JHT/USWRP	Continual	Tropical storms	Tropical- extratrop. interactions	Large-scale environmental flow
MSC/CANADA	Continual	Ensemble forecast exchange/researc h	Statistical post-processing	Multi-center ensembles
PACJET/USWRP	Continual	Short-range forecast research	Integrated forecast approach	Influence of large scale environment
RAP/NCAR	Continual	Societal applications	Transfer science to private sector	NWP applications

Table 1: Anticipated NOAA THORPEX collaboration with other programs and organizations. See Appendix (section 5.3) for list of abbreviations.

Collaboration with other programs – Benefits. THORPEX will use the scientific and technological expertise, observing, phenomenological and other capabilities that other research and development programs can offer to enhance respective NWP methods in the end-to-end forecast process. A NOAA THORPEX Research Program priority is collaboration with field programs where new observing systems are tested and/or data valuable for NWP experimental use are collected. Since these are generally very expensive programs, any collaboration with such existing or planned programs is critical for providing the maximum resources for other vital THORPEX research.

4.1.6 PROGRAMMATiC ACTIVITIES

All funding for grant-based external and internal NOAA THORPEX research and related real-time testing and demonstration will be distributed via peer-reviewed proposals, in the direct interest of advancing NOAA's THORPEX service goals. This will include collaborative and joint work with other THORPEX activities and other programs.

In the coarse of the collaborative THORPEX program, NOAA may wish to contribute to efforts that do not directly serve its THORPEX service goals but is likely to benefit NOAA or the broader community in other ways. Also, service applications developed outside of NOAA's THORPEX goal of improved 3-14 day weather forecasts will have to be adapted and evaluated for possible use in NOAA operations. Proposals for these activities will also go through the same peer review process described in Sections 4.1.2 and 4.1.3 except criterion 2 for these programmatic proposals will be modified:

2) **Relevance to the US, North American, or International THORPEX science and service goals**. Ability to demonstrate how the research results will lead to improved forecast skill or will support other activities achieving that goal (40%).

4.2 WORK PLAN

The scientific research and supporting core activities described in sections 3.3 and 4.1.3 will be carried out according to the time schedule (ST - short term, 1-4 years; MT – medium term, 5-7 years; and LT – long term, 8-11 years) indicated there. The related activities, with their relative role in the integrated research program, are summarized in Table 2.

4.3 DELIVERABLES

The deliverables of the THORPEX program, which will depend on the availability of appropriate funding levels, can be summarized as follows:

1) THORPEX will deliver a set of new observational, data assimilation, numerical modeling, ensemble, and user application techniques according to the time-lines in Table 2. By the end of the THORPEX program, these techniques will form a complete set of procedures for the implementation of the new, integrated, dynamically controlled, and adaptive NWP process into weather forecast operations.

2) The introduction of the new integrated NWP process will accelerate the rate of improvement in NWP forecasts. It is expected that the current rate of half- and 1-day improvement in 3 and 8-day forecasts per decade (see Fig. 7) will be doubled to 1- and 2-day improvements, respectively.

3) The acceleration of NWP skill improvements will be achieved in the most cost-effective way. The overall societal benefits resulting from the implementation of the new and integrated NWP procedures will outweigh the incremental cost of their implementation.

THORPEX Service Goal. Due to the lack of skill, NOAA currently issues no daily precipitation forecasts beyond 3 days and no daily weather forecasts beyond 7 days lead-time. With the anticipated acceleration of improvement in forecast skill, THORPEX research will accomplish the stated NOAA THORPEX related service goal of *introducing skillful 3-7 day precipitation and 8-14 day daily weather forecasts*. Thus, the development and implementation of the THORPEX integrated NWP forecast process constitutes a major contribution to achieving NOAA's strategic goal of "Advancing short-term warning and forecast services", which in turn will lead to significant benefits to a wide range of users.

SUBPROGRAM \ PERIOD	2004-07	2008-10	2010-14	TOTAL	Appr. %
OBSERVATIONS	20.0%	20.0%	20.0%		20.0%
New instruments/platforms	8.0%	6.0%	4.0%		6.0%
Intelligent sensors, adaptive observing	7.0%	7.0%	4.0%		6.0%
Remotely sensed data processing	5.0%	7.0%	12.0%		8.0%
DATA ASSIMILATION	20.0%	20.0%	20.0%		20.0%
Techniques for new/existing data types	8.0%	5.0%	5.0%		6.0%
Advanced error covariance information	6.0%	8.0%	5.0%		6.3%
Adaptive observing techniques	6.0%	7.0%	10.0%		7.7%
FORECAST PROCEDURES	20.0%	20.0%	20.0%		20.0%
Initial ensemble perturbations	8.0%	4.0%	2.0%		4.7%
Model vs. initial value related errors	8.0%	6.0%	4.0%		6.0%
Representling model error in ensembles	4.0%	10.0%	14.0%		9.3%
APPLICATIONS	20.0%	20.0%	20.0%		20.0%
Enhance frecast information content	8.0%	6.0%	4.0%		6.0%
Assess forecast costs	7.0%	5.0%	3.0%		5.0%
Assess forecast benefits	5.0%	8.0%	10.0%		7.7%
Develop adaptive forecast applications		1.0%	3.0%		1.3%
CROSS-CUTTING ACTIVITIES	20.0%	20.0%	20.0%		20.0%
Determine global NWP data needs	10.0%	2.0%			4.0%
Identify optimal instruments/platforms	6.0%	4.0%	2.0%		4.0%
Assess value of 4 sub-components	3.0%	10.0%	4.0%		5.7%
Design cost effective forecast process	1.0%	4.0%	14.0%		6.3%
TOTAL (in Millions of $US)	14.75	18.00	16.00		48.75
%	30.3%	36.9%	32.8%		100.0%

Table 2: Relative contribution of research tasks under the four NWP sub-components and the cross-cutting activities, as a fraction of total funding available for external research grant programs.

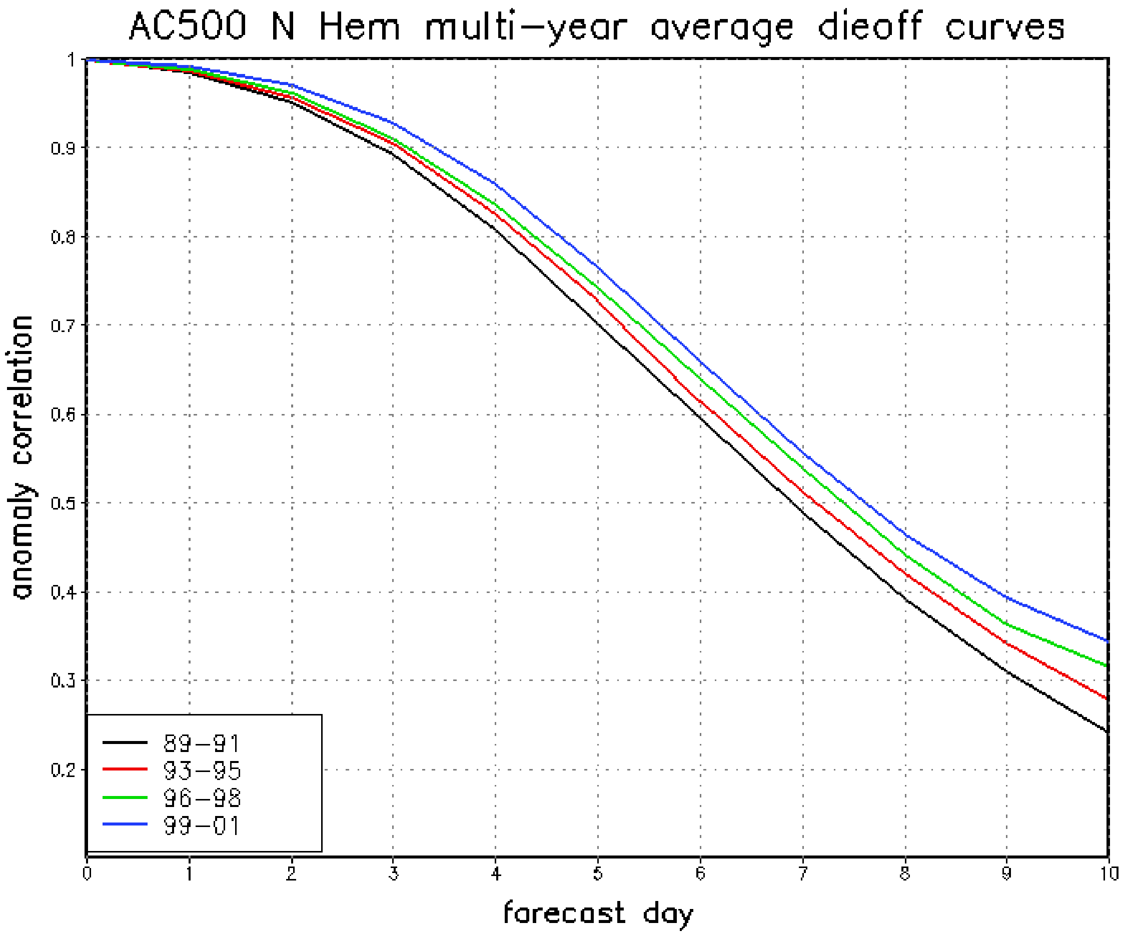

Fig. 7: The improvement in the skilll (Pattern Anomaly Correlation) of operational NCEP NWP 500 hPa geopotential height forecasts over the Northern Hemisphere extratropics during a recent 10-year period. Courtesy of Pete Caplan of EMC/NCEP/NWS/NOAA.

4.4 PERFORMANCE MEASURES

The success of the program in relation to the three deliverables will be measured as follows:

1) The delivery of new observing, data assimilation, forecast, and application methods and procedures, each demonstrably capable of providing the desired skill, functionality, or speed, and each ready to be implemented into the operations of NOAA and other interested agencies according to the time schedule in Table 2;

2) An assessment of whether the level of forecast improvements during the THORPEX decade exceeds that in the preceding decades, based on standard NWP forecast verification measures with a long historical track record such as 500 hPa

geopotential height Pattern Anomaly correlation (PAC), Root Mean Square (RMS) error, and Equitable Threat Score (ETS) of accumulated precipitation forecasts. The integrated nature of THORPEX research and development work mean the overall forecast improvement can be measured only after most research activities are completed, near the end of the program;

3) Delivery of methods for assessing the incremental costs and benefits associated with the use of the new forecast methods proposed by THORPEX.

The overall success of the NOAA THORPEX program will be measured in a unique and comprehensive way. The program will be considered successful if the newly developed cost/benefit analysis tools (point 3 above) indicate that the forecast improvements (point 2) due to the new THORPEX procedures (point 1) can be achieved operationally in a cost-effective manner. That is, the incremental economic and societal benefits associated with the use of the new THORPEX forecast procedures would outweigh their implementation and maintenance costs.

4.5 BROADER IMPACT ON SCIENTIFIC RESEARCH

With the adoption and development of a cost/benefit analysis as an integral part of a research program, THORPEX and NOAA will set an example that can be followed by other programs and agencies regarding the evaluation of the societal benefits of scientific research programs. For example, the comprehensive evaluation of the end-to-end forecast process in the 3-14 day time range will allow for a cost-benefit analysis of changes due to the introduction of not only the entire new THORPEX paradigm, but also its four individual sub-components. At present, only limited information is available regarding the potential relative contribution of improvements due to the four subcomponents (see Fig. 8).

A systematic cost-benefit analysis may reveal that certain forecast components may have a considerably larger effect on 3-14 day forecast improvements than others. Such results can provide important input when a rational reallocation of long-term research and operational priorities and resources is considered, making the operations of agencies like NOAA more cost-effective.

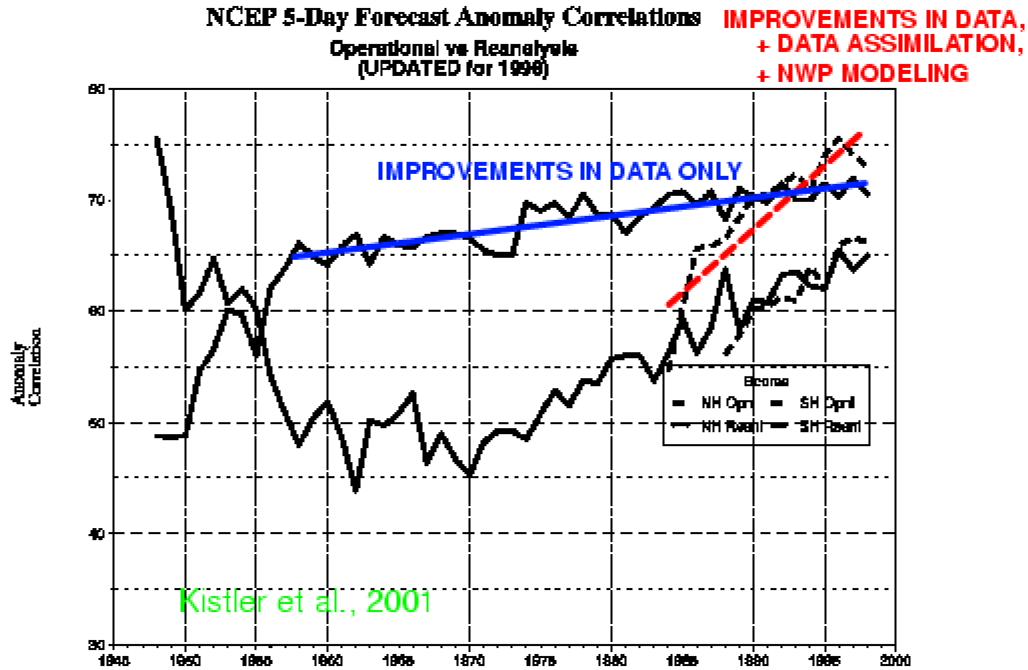

Fig. 8: Annually averaged Pattern Anomaly Correlation (PAC) for 5-day lead-time forecasts for the Northern (upper continuous and dashed lines) and Southern Hemisphere extratropics (lower lines) with a frozen data assimilation and NWP modeling system ("reanalysis" configuration, continuous line, and blue linear interpolation line for NH) and with an operationally evolving NWP data assimilation/modeling system ("operational" configuration, dashed line, and red linear interpolation line for NH). While both curves show an increase in skill due to enhancements in data quality and quantity, the red curve exhibits a much faster improvement due to continual updates to the NWP data assimilation and modeling systems.

4.6 EDUCATION AND OUTREACH

Since THORPEX is a long-term program with the goal of developing a new forecast paradigm to be used 10-15 years from now, related educational and outreach activities are especially important:

1) First, today's students have to be prepared so they can join the ongoing research efforts, and be able later to take advantage of the new operational activities and opportunities. NOAA'a extramural research grant program that will support research efforts at universities and other research facilities is expected to entrain talented students and thus contribute to successfully preparing the next generation of experts in the research and operational areas of weather

forecasting (see Section 4.1.2).

2) Second, the expert and the lay weather forecast user community will have to be well prepared for the introduction of new probabilistic forecast formats and the new adaptive forecast procedures. The societal and economic benefits component of the NOAA THORPEX Program (see Application part of the Science Plan in Section 3.3) will contribute to this objective through extensive collaborative efforts with different parts of the user community.

4.7 PATH TO OPERATIONS

Since the major goal of THORPEX is to accelerate advancements in NWP forecasting, a high priority is the testing and implementation of the new techniques and procedures in an operational environment. It follows from the application oriented science goals of THORPEX that success can be assured only if operational needs are carefully considered at each step of the research process, including planning, exploration, development, testing, and implementation. Research activities must be conceived as part of the overall NWP oriented THORPEX program, not as isolated scientific initiatives. Each research activity must address and enhance parts of the new NWP forecast paradigm, considered in its entirety as an end-to-end process. Only this will ensure that all THORPEX funded activities contribute to the THORPEX goal of the development of a new, integrated, and cost-effective NWP process ready to be implemented at operational NWP centers.

The strong involvement of NOAA’s operational NWP forecast center (NCEP), and most importantly, the creation and use of an associated operational test facility (ONTF), will allow the formal testing and subsequent introduction of new THORPEX research results into the operational environment. The role of the ONTF will be critical in ensuring that in each phase of the THORPEX program emerging new research results will find their way into operations without any delay. A series of such implementations, in parallel with in-house NOAA efforts is expected to significantly contribute to achieving NOAA’s THORPEX Service Goals of introducing operational 3-7 day precipitation and 8-14 day daily weather forecasts.

4.8 BUDGET

Since the major NOAA THORPEX goal is the development of an integrated NWP forecast process where the two-way interactions among observing, data assimilation, forecasting, and user application procedures elevate NWP forecasting to a new level of integrity and efficiency, it is critical to secure adequate funding to address each aspect of the forecast process. It follows from the integrated nature of the research process that a lack of funding for one part of the program may jeopardize the success of the program as a whole. However, adequate NOAA funding will allow for the development of a healthy US research effort that can significantly contribute to the international THORPEX program.

The NTEOC anticipates that funding will be available at the following level:
2004 (Year 1) $2M
2005 (Year 2) $5M
2006-2014 (Years 3-11, per year) $10M

BUDGET ITEM\PERIOD	2004	2005	2006-7	2008-10	2011-14	TOTAL	%
RESEARCH GRANTS							
External	$1.00	$2.75	$5.50	$6.00	$4.00	$48.75	50.26%
Internal	$0.30	$0.60	$1.40	$1.20	$0.60	$9.70	10.00%
INFRASTRUCTURE							
Testing Facility	$0.20	$0.80	$1.50	$1.40	$1.50	$14.20	14.64%
Real-Time Test	$0.30	$0.50	$1.20	$1.00	$3.50	$20.20	20.82%
Meetings / Travel	$0.10	$0.20	$0.20	$0.20	$0.20	$2.10	2.16%
MANAGEMENT							
Staff / Other costs	$0.10	$0.15	$0.20	$0.20	$0.20	$2.05	2.11%
TOTAL	$2.00	$5.00	$10.00	$10.00	$10.00	$97.00	
%	2.06%	5.15%	10.31%	10.31%	10.31%		100.00%

Table 3: Estimated budget for research grants, infrastructure, and management costs for the entire life of the NOAA THORPEX program (per year, in Millions of $US).

Each year, at least 50-60% of these funds is expected to be used for supporting extramural research efforts as part of a THORPEX Research Grant program. If opportunities arise, some of the AOs will be issued and evaluated in coordination with other agencies (e. g., NSF). Of the overall budget ($96.3M), approximately 5% will be needed to continually upgrade data communication capabilities and to establish and maintain an efficient data base; 10% for the establishment and operation of the National Operational NWP Test Facility (NONTF); 20% for a major real-life test of the new THORPEX end-to-end forecast paradigm, including an extensive field program if necessary; 3% for organizational expenses such as workshops, management staff salary, etc.; and 7% for enhancing existing NOAA research programs so they can actively participate in the THORPEX program and support or collaborate with extramural researchers.

Table 3 contains an estimate of the budget numbers broken down for each task and major time period. Note that the NOAA THORPEX Grant Program expects to distribute funding equally among research projects in the four main sub-programs. This is a prudent approach to follow since there is no substantial scientific evidence on what benefits enhanced research efforts in any of the four sub-programs might bring relative to the others. Reallocation of resources will be possible after the major part of the THORPEX research is completed. For further budget details on this aspect of the program, see Table 2 in Section 4.2.

Note that the line “Testing facility” contains the combined budget for the first three items listed in Section 4.1.4 (Data communication, data base, and Operational NWP Test Facility). Since the ONTF will be used by not only the THORPEX but also the wider NWP research community, the budget for the ONTF assumes that the computational costs associated with the ONTF will be covered from other sources. Depending on the number of its users, the ONTF may assess a modest fee, paid out of the research grants, to partially cover its personnel costs. Because programmatic activities (Section 4.1.6) are beyond the control of the NOAA THORPEX program the related costs are not listed explicitly in Table 1. The NOAA THORPEX program will appropriate necessary funds to cover such expenditures, up to 5% of its total budget. Since the largest programmatic expenditures will likely be connected with international field programs, funding for all programmatic activities will be considered as part of the Real-time test and demonstration budget item.

5. APPENDIX

5.1 LINK WITH NOAA’S STRATEGIC GOALS

NOAA’s THORPEX goal of improved 3-14 day weather forecasts is directly linked with NOAA’s 3rd Mission Goal of serving “*Society’s needs for weather and water information”* (Strategic Plan, NOAA 2003). In addition, the THORPEX program is expected to contribute in a significant way to establishing NOAA’s new priorities for the 21st century. Thus NOAA’s THORPEX Research Program conforms in all major aspects with NOAA’s Strategic Plan.

> *The 3rd Mission Goal of the Strategic Plan states NOAA will “provide integrated observations, predictions, and advice for decision makers to manage … environmental resources.”*

THORPEX fully embraces this goal by promoting a new forecast paradigm where the four sub-components of the forecast process are fully integrated (section 2.3). We note that the four forecast subcomponents of the THORPEX program correspond to the first four *“mission strategies and measures of success*” as defined in the Strategic Plan:

NOAA MISSION STRATEGY	THORPEX FORECAST PROCESS COMPONENT
Monitor and observe	Observations
Understand and describe	Data assimilation
Assess and predict	Forecasting
Engage, advise, and inform	Applications

> *The 3rd Mission Goal defines the “Outcome measures” as (1) the “increased accuracy and amount of lead-time”, and (2) “increased satisfaction with and benefits from NOAA information and warning services”.*

The anticipated achievements of the THORPEX program (Section 4.3) are assessed by the same measures of "*quality of service and benefits*" identified in the Strategic Plan: increased skill and amount of lead-time, and overall societal benefits. NOAA's THORPEX initiative intends to be one of the first research programs that will measure success in terms of whether the overall societal benefits due to the newly developed forecast methods outweigh the associated implementation and maintenance costs (section 4.4).

Highlights from the 3rd Mission Goal of the Strategic Plan, that THORPEX fully embraces, include:

1) *"Cost effective observation systems" – More observations:*
    a. *Obtained from international and domestic partners*
    b. *Archived, available and accessible*
    c. *From new multi-use observing systems*
    d. *With improved effectiveness*

The activities and tasks described in the Observations and Cross-cutting sections of the Science Plan (Section 3.3) directly address the above priorities of the Strategic Plan.

2) *"Shortened cycle times from research (government and academic) to operations (e. g., models, technology, and techniques)" for "Improved accuracy of weather … models"*

THORPEX has been conceived from the start as an application-oriented research program with a clear focus on transferability of results into operations. All phases of the program will be conducted in this spirit, assuring that its research efforts will lead to more accurate operational weather forecasts (see section 4.6).

3) *"Improve forecast and warning capabilities to reduce uncertainty and increase economic benefits":*
    a. *Enhanced use of observations*
    b. *Increased volume of information on forecast uncertainty (probabilities)*
    c. *Improved performance of weather and water prediction suite*
    d. *Increased training of users*

All these are key aspects of the THORPEX program as discussed in different parts of the Science Plan (see Section 3).

4) *"Bridging weather and climate time scales, NOAA will continue to collect environmental data and issue forecasts and warnings".*

By focusing on the medium- and extended weather prediction ranges NOAA's THORPEX efforts will aim at bridging the gap that currently exists between weather and climate forecasting from the weather forecasting perspective (see Section 3). By collaborating with climate programs such as CLIVAR and GAPP (see section 4.1.5), THORPEX expects to optimize the use of observational and other resources to contribute to a more economical and seamless future suite of weather and forecast products.

5) "*Promote appropriate responses to hazardous weather- and water-related conditions, in order to enhance human preparedness", including "increased assistance to international partners".*

The application part of the THORPEX program is designed to promote such activities, both on the national and international level (see Sections 3.3 and 3.4).

The THORPEX program will also serve and promote four of NOAA's six Cross-cutting Priorities as defined by the Strategic Plan:

1) *"Integrated global environmental observation and data management system"*

THORPEX is expected to contribute to this goal by better defining the observational needs of weather forecasting and coordinating these needs with those of other NOAA and extramural application requirements, including those of climate monitoring (see the Observations parts of Section 3)

2) *"Environmental literacy, outreach, and education", through improving " awareness of [NOAA's] mission goals and accomplishments, as well as basic knowledge of the environment and human interactions with it"*

Through careful scientific studies, and the active involvement of user groups the Applications sub-component of the THORPEX program is dedicated to carry out an aggressive outreach program to existing and potential new users (see Application parts of Section 3). At the same time, the THORPEX program will promote and deepen the level of interaction with academic scientists and their students through NOAA's extramural THORPEX Research Grant program (see Sections 4.1.2 and 4.6).

3) *"Sound, state of the art research" with an "increase [in NOAA] investments in short- and long-term research and in development", with an emphasis on accelerating "the transfer of knowledge and technology into operational use":*
    a. *"Increased interactions among NOAA researchers, operations, and resource managers;*
    b. *Increased use of models and assessments … inside and outside NOAA"*
    c. *Increased transfer of NOAA models, forecasts, products, and services from research into operations"*

These points in the Strategic Plan serve as the guiding principles of the THORPEX program. Through a coordinated, long-term research program THORPEX will revolutionize the process of weather forecasting by delivering new techniques, methods, and procedures that are ready for operational implementation, and will yield *"increased accuracy in [operational] predictions and assessments"* (see Section 4.6).

4) *"International cooperation and collaboration"*

THORPEX is an international program that, given the complex and global nature of weather forecasting, cannot succeed without the participation of a large number of countries. The THORPEX program will enable NOAA to fully realize the benefits of, and provide the maximum contribution to international collaboration in the area of weather forecasting (see section 2.3.4).

In addition, "NOAA will continue to seek out, build, and support strategic partnerships with [other] agencies, the private sector, academia, and non-government organizations"

THORPEX recognizes that to assess and predict "*evolving national needs*" the end-to-end forecast process should be considered as a loop where the needs of our user partners can feed back into the forecast process in both the research and operational environment (see Sections2.3.1 and 3.1). Collaboration and partnership, therefore, is paramount to the success achieving NOAA's Strategic Goals.

5.2 LINK WITH THE NWS STIP PROCESS

Since THORPEX is an application oriented long-term research program aimed at improving operational weather forecast procedures it is important that NOAA's participation is coordinated with the Science and Technology Infusion Plan (STIP) of the National Weather Service, which is the operational arm of NOAA's weather forecast activities. NOAA's THORPEX program conforms with all the important aspects of the STIP process established recently at the NWS, as illustrated with the following examples:

1) *STIP expects that the operational requirements will motivate all aspects of service oriented research efforts, including planning and budgeting.*

Since its start, scientists from operational centers, including NCEP/NWS, have participated in the THORPEX planning process both on the national and international levels. The inclusion of scientists and executives as leading members of the NOAA THORPEX Executive Oversight Committee and the NOAA THORPEX Science and Implementation Team ensures that the service priorities of NOAA's THORPEX program will be considered in every phase of the program (see Section 4.1.1).

2) *STIP emphasizes the need to establish a "thread to operations" early on. Every service oriented research effort should have a plan for inserting its results into operations.*

A major emphasis of NOAA's THORPEX program is the promotion of research that either leads to operational applications or demonstrably supports activities facilitating such applications (see Sections 4.1.1 and 4.7).

3) *STIP supports the establishment of an NWP test facility with the aim of*

streamlining the transition of research results into operations.

NOAA's THORPEX plan identifies the establishment of a National Operational NWP Test Facility as an essential part of the program, facilitating the flow of extramural contributions into the operational environment (see Section 4.1.3).

4) *STIP views weather forecasting as an end-to-end process where research planning starts with an analysis of operational shortfalls and requirements, and works backward to identify corresponding research foci.*

The NOAA THORPEX Research Plan follows the STIP process closely. The plan first identifies improvements in 3-14 day precipitation and weather forecasts as the primary service goal (Section 2.1), upon which the rest of the research plan is based.

5) *According to STIP, feedback, coordination, and cross-cutting activities are extremely important in connecting the four major areas (observations, data assimilation, forecasting, and applications) of the forecast process.*

NOAA's THORPEX program fully embraces this view by aggressively pursuing research activities that cut across the boundaries between the four NWP sub-areas also identified by STIP, with the aim of establishing the new, integrated forecast paradigm of the next decade (Section 3).

5.3 CONTRIBUTORS

NOAA's THORPEX initiative started with a NOAA THORPEX Tiger Team Meeting (August 6 2002). The NOAA THORPEX Research Program Plan is based to a large extent, on the work of a NOAA THORPEX Planning Meeting (October 21-22 2002), with input from the NTSIT.

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Jim Hansen	MIT	Marty Ralph	NOAA/ERL

5.4 ACKNOWLEDGEMENTS

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5.6 LIST OF ACRONYMS

AFWC	Air Force Weather Center
AO	Announcement of Opportunity
CDC	Climate Diagnostics Center
CIMSS	Cooperative Institute in Meteorological Satellite Studies
CIRA	Cooperative Institute for Research in the Atmosphere
CLIVAR	International Research Programme on Climate Variability and Predictability
CSPP	Cold Season Precipitation Program
DOC	Department of Commerce
DOD	Department of Defence
EMC	Environmental Modeling Center
ERL	Environmental Research Laboratory
ETS	Equitable Threat Score

FGGE	First GARP Global Experiment
FNMOC	Fleet Numerical Meteorology and Oceanography Center
FSL	Forecast Systems Laboratory
GAPP	GEWEX Americas Prediction Project
GARP	Global Atmospheric Research Program
GEWEX	Global Energy and Water Cycle Experiment
GSFC	Goddard Space and Flight Center
HPC	Hydrometeorological Prediction Center
ICSC	Internatinoal Core Steering Committee
IHOP	International H2O Project
IPO	Integrated Program Office
ISSC	International Science Steering Committee
JCSDA	Joint Center for Satellite Data Assimilation
JHT	Joint Hurricane Testbed
LT	Long Term (7-10 years)
MT	Medium Term (4-6 years)
NASA	National Aeronautics and Space Agency
NCEP	National Centers for Environmental Prediction
NCO	NCEP Central Operations
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NRC	National Research Council
NRL	Naval Research Laboratory
NSF	National Science Foundation
NTEOC	NOAA THORPEX Executive Oversight Committee
NTSIT	NOAA THORPEX Science and Implementation Team
NWP	Numerical Weather Prediction
NWS	National Weather Service
OAR	Office of Oceanic and Atmospheric Research
ONR	Office of Naval Research
OGP	Office of Global Programs
ONTF	Operational NWP Test Facility
OSSE	Observing System Simulation Experiment
OST	Office of Science and Technology
OWAQ	Office of Weather and Air Quality
PAC	Pattern Anomaly Correlation
PACJET	Pacific Landfalling Jets Experiment
RCSC	Regional Core Steering Committee
RMS	Root Mean Square
RSSC	Regional Science Steering Committee
SQ	Scientific Questions
STIP	Science and Technology Infusion Plan
TOST	THORPEX Observing System Test
ST	Short Term (1-3 years)

WSR Winter Storm Reconnaissance